    b. In 1665 switched to elliptical after Cassini's efforts in Bologna provided high quality empirical evidence for bisected eccentricity, in the process removing one of the shaky steps in Kepler
    c. System not a serious contender for various reasons, among them a large number of calculation errors; but book of interest because of its extensive review and critical analysis of others
3. The simple elliptical hypothesis, with equant point at the other focus, continued to be put forward in spite of Kepler's explanation in the *Epitome* of why it does not work
    a. Ward, ironically, was criticizing Boulliau in order to justify resorting to equant, as he did in 1656
    b. Boulliau's 1657 reply showed that the equant is not empirically satisfactory
    c. Pagan nevertheless published Keplerian elements with equant at focus that same year
4. Wing (*Harmonicon coeleste*, 1651; *Astronomia instaurata*; 1656, Ephemerides for 1659-1671, 1658; *Astronomia Britannica*, 1669) adapts Boulliau's original method of calculating the equation of center, while abandoning completely Boulliau's geometrical cosmology and cone ("a mere supposition")
    a. "No such thing in nature as mean motion" -- an openly calculational approach, with no concern for underlying physics in 1651
    b. Actual construction akin to an oscillating equant point in 1651 (just as Kepler said was necessary), yielding reasonable agreement with observation (Wing's first method)
    c. Shifts to different method in 1656 and 1669, in which an empirically based geometrical correction term used to relocate planet, different from Boulliau's, but in same spirit
    d. (Tries to conflate Kepler and Cartesian vortex in 1669)
5. Two other important approaches eschewing the area rule published in England between 1660 and 1676, by Streete and Mercator, will be discussed below
6. One thing to notice in all these attempts is that nothing emerges to show Kepler wrong
    a. Ellipse becomes conceded, constituting a form of assimilation of Kepler, as does accuracy comparable to area rule, which requires some special contrivance or other in each case
    b. Notice also that Tycho's data the empirical base for these efforts, with no attempt to use either new data or discrepancies between Kepler and observation to generate better accounts, in the way Horrocks did, making these efforts less an assimilation of Kepler than his was

C. The Development of the Pendulum Clock

1. The limited accuracy of clocks -- e.g. Tycho's observations involve as much as 1/4 hour error in time -- was holding back astronomy in two respects:
    a. Some observations were simply being misstated -- direct measurements of latitude and longitude at a specified time (as opposed to measurements relative to certain nearby stars)
    b. Lack of standardization impeded simultaneous measurements at different sites, as well as comparison of measurements at slightly different times
2. Although Galileo had proposed ways of turning the pendulum into a clock, Huygens was the first to produce a completely functioning pendulum clock in 1656 (announced in his *Horologium* of 1658)

    a. Unlike Riccioli, no need for a human to count the number of pendulum arcs out loud -- a complete mechanism, with the pendulum driving gears and the gears driving the hands of a clock
    b. Some key features: an "endless chain" that allows the clock to be wound without disturbing its time-keeping, and an easily actuated means for making small corrections to the period
    c. Immediately reduced the error in time from as much as 15 min per day drift down to 10-15 seconds per day
3. Huygens continued to improve his 1656 clock over the next few years, inventing a series of variations to it; throughout these efforts he generally turned his designs over to professional clock-makers, who then produced and marketed the clocks
    a. He measured the non-isochronism of his basic pendulum clock, finding that it deviated by 5 sec per day with a 1 to 2 deg arc and 18 sec per day with a 5 to 6 deg arc
        (1) This led him to try curved walls along the pendulum chord, effectively shortening the length at larger arc
        (2) This increased accuracy so long as the arc remained true, but lateral displacement of the arc re-introduced inaccuracies
        (3) He then reverted to a circular pendulum, introducing a mechanism restricting it to small arcs
    b. In 1659 Huygens discovered the theoretical shape of the curved wall needed to make the period independent of the arc length, namely a cycloid
        (1) Specifically, cycloidal cheeks produce an isochronous cycloidal path, as explained in his *Horologium Oscillatorium*, published in 1673
        (2) After 1659 Huygens always employed cycloidal cheeks on his pendulum clocks, yielding accuracies within a few seconds per day
        (3) Cheeks also on his maritime clocks, which he developed in an effort to solve the problem of determining longitude at sea
    c. In the late 1670s Huygens also invented the spring-balance clock, apparently in an effort to get around the problem of ships' motion disturbing his pendulum clock
        (1) Was about to conduct sea trials with this when he discovered that spring-balance sensitive to variations in temperature
        (2) In spite of 40 years of effort, Huygens never solved the problem of keeping accurate time at sea, though his failure was not entirely clear to him at the time he died in 1695
4. Once the promise of the pendulum clock became clear, many other inventors refined and developed it, leading to a large number of variations of the basic idea
    a. For example, the clocks at Flamsteed's Greenwich Observatory were designed by Tompion, who became the leading clock designer in England
    b. The Greenwich clocks used 13 ft adjustable circular pendulums, giving a 2 second arc (4 sec period)

        c. {Few followed Huygens in using cycloidal cheeks; instead they restricted the motion to small or constant arcs}
    5. By 1670, the pendulum clock had become standard throughout astronomy in one version or another, allowing extreme high confidence in measurements of time; 15 arc second per second error in time
        a. Most of the clocks could maintain accuracy to within a few seconds per day, and they were easily correctable, allowing them to be reset by astronomers as called for
        b. Note Flamsteed's remarks about the Tompion clock (p. 140): in March it was found to lose 18 sec per day, in September, to gain 13 sec per day -- e.g. a 0.02% error
        c. Careful calibration -- via resetting of the pendulum length -- on the best of these clocks -- e.g. Huygens's -- could reduce the error another order of magnitude

D. Advances in the Astronomical Telescope
    1. During the 1640's the Keplerian or astronomical telescope had been made longer and longer, each increase in aperture leading to an even greater increase in length
        a. Long wooden tubes, but could be focused to eliminate lens misalignment effects
        b. Their long focus permitted much higher magnifications, with reduced chromatic effects
    2. Huygens made a major breakthrough in extending the length of telescopes in the mid 1650's when he invented the aerial telescope, abandoning the long wooden tube and instead using two separate pieces, aligned with one another, separated by open air
        a. A 123 ft telescope, with a 7.5 inch aperture: 50 power with comparatively little aberration
        b. In part because of the open-air effects of this arrangement, Huygens was the first to discuss "seeing" phenomena -- i.e. visual disturbances due to temperature oscillations in the air
        c. Huygens added light dusting of lenses with coal dust to reduce aberrations
    3. Just as important as the improved optics, Huygens in the late 1650's also added markings allowing direct measurement of angular distances between objects
        a. Gascoigne had invented the micrometer earlier, but it had been lost, and Hooke invented one at roughly the same time as Huygens, but Huygens's micrometer as announced in *Systema Saturnium* had more impact
        b. Combination of higher magnification and micrometer allowed precise measurements of observed sizes, though still handicapped to some extent by the glow around the edges from chromatic aberration
    4. Huygens added the compound negative eyepiece still named after him in the early 1660's -- i.e. he put two convex lenses together in the eyepiece of his aerial telescope
        a. With suitable spacing between the two lenses, get a reduction -- more accurately, a correction -- of chromatic aberration
        b. Net effect was that the astronomical telescope had become a developed technology by the mid-1660's allowing not only much higher magnifications, but clearer images too

5. As with the clock, others picked up Huygens's inventions, extending and improving them
    a. The screw micrometer was developed in Paris in the mid 1660's by Picard and Auzout, allowing a very precise measure of subtended arcs
    b. Cross-hairs were introduced, which together with proper collimation allowed precise measurements of observed positions
    c. Improved lenses were being offered by many, with the best ones by Campani (initially in Rome)

E. Huygens's *Systema Saturnium* (1659)

1. Using telescopes incorporating his initial improvements, Huygens made two key discoveries concerning Saturn in the mid-1650's -- the first truly major discoveries since those of Galileo in the second decade of the century
    a. Saturn has a satellite -- Titan (1655)
    b. Bulges in Saturn are in fact rings (1656)
2. The discovery of the first satellite of another planet offers a further opportunity to pursue empirical cross-checking through developing orbital elements
    a. Huygens himself publishes careful data on "the uniform movement" of the Moon of Saturn (p. 264)
    b. Titan's eccentricity small (0.029), but not so small as those of the satellites of Jupiter
    c. No opportunity to check Kepler's third "law" until after Cassini discovers two more satellites, in early 1670's (not confirmed in England until after 1685)
3. Huygens's discovery of Saturn's rings was more a matter of clever detective work, using the varying descriptions of his predecessors over a 40 year period, than it was a product of the superiority of his telescopes
    a. An example of the interpretive element in observation, for once learn to see the protrusions as rings, they appear to us to be rings
    b. Huygens's detective work summarized in diagram (p. 309) showing the different appearances of the rings, vis-a-vis the Earth, when Saturn is at different positions in its orbit
    c. Significantly improved telescopic observation of the rings, using Campani telescopes, plus right timing, revealed the Cassini divide in 1675
4. Huygens's discoveries were initially presented as evening papers to the famous Rohault discussion group, helping to make him the lead figure in this group following the death of Gassendi in 1655 (the group Molière fictionalized in his satire *The Learned Ladies* in 1672)
    a. *Systema Saturnium* published in 1659, including the results on Saturn and a description of the micrometer he had incorporated (pp. 228-231)
    b. Follow-up publications supporting the original in 1660, adding subsequent observations of Saturn in 1668, and determining orbital characteristics of the three known satellites in 1673
5. Few of Huygens's subsequent efforts lay within observational astronomy, but his contribution on

Saturn, much like those of Galileo in 1610-1620, showed that advances in the telescope had opened the way to a new round of discoveries

    a. All the technical complications and headaches associated with new telescopes worth the effort
    b. And, although comparatively few measurements, enough to provide a major impetus toward the telescope becoming an indispensable instrument of measure in astronomy -- the beginning of the end of Tycho's standard

III. Astronomy in a New Context: 1650s to 1670s

- A. Cassini on the Sun and on Jupiter and its Satellites
  1. Huygens was not the only person to be taking advantage of the improvements in the technology of the astronomical telescope in the late 1650's; Cassini was doing so too, along with other things
     a. Cassini joined Bologna faculty in 1650, where he was a colleague of Riccioli and Grimaldi
     b. During the 1650's he initiated a careful effort on the motion of the Sun, measuring meridian altitudes throughout the year using a specially constructed large gnomen at San Petronio
     c. As part of this effort, carried out impressively precise measurements to confirm Kepler's bisection of the Earth-Sun orbit (convincing Riccioli, as well) (see Heilbron, pp. 102-119)
     d. These results revealed a discrepancy in the position of the celestial equator that led him to question both the solar parallax and refraction corrections used by Tycho
     e. (Horrocks had questioned these for reasons having to do with discrepancies in Kepler's orbits)
  2. In the late 1650's Cassini began using telescopes by Campani, with truly superior lenses -- the highest quality of the era (along with Divini's), which others tried in vain to match
     a. In the early 1660's established that Mars, Venus, and Jupiter rotate on their axes, with Mars having a period a little longer than 24 hours and Venus a little under 24 hours (1666)
     b. Also confirmed a conjecture by Hooke that Jupiter is slightly flattened -- he estimated by 14/15
  3. In 1650 undertook the project of working out detailed orbits for the four Galilean moons of Jupiter
     a. Others had determined periods and some elements, but precise distances from Jupiter could not be established without a micrometer; Kepler's suggestion that his third law holds for these satellites amounted to nothing more than that the periods are somewhere between the first and third power of the radii
     b. 15 years of observations, beginning with a copy of Torricelli's telescope in 1652, but making his most rapid progress in 1664 with the aid of 17 foot and 34 foot telescopes by Campani
     c. Able then to observe shadows of the satellites on Jupiter, from which he could determine velocities to a much higher accuracy
  4. Cassini's tables giving ephemerides of the satellites of Jupiter were published in 1668, the first detailed accurate account of these orbits; useful for determining longitudes from eclipses
     a. Adopted circular orbits with uniform circular motion throughout, which he could get away with in the case of these four (e=0.000, 0.000, 0.002, 0.008)